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Characterizing Saline–Sodic Soils in a Semi-Arid Floodplain: Implications of Soil Texture on Salinity and Alkalinity in Tuoketuo County, Inner Mongolia

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Abstract. Soil salinization and alkalization threaten agricultural productivity in arid and semi-arid regions, particularly in Inner Mongolia. This study investigates the spatial variability of salinity and alkalinity in Tuoketuo County, located in the Yellow River floodplain, where saline–sodic soils are widespread. Soil samples were collected across varying distances from the Da Hei He river channel and from both natural and remediated or cultivated lands, and analyzed for key soil physicochemical properties, including electrical conductivity (EC), pH, cation exchange capacity (CEC), exchangeable sodium (Na^+), and particle size distribution. Results showed no significant variation in EC or pH with depth but revealed strong associations with soil texture. EC was negatively correlated with sand content and positively with clay, while pH showed a moderate positive correlation with clay content. The patterns suggest that soil texture is a controlling factor of salinity and alkalinity across these soils, likely through its effects on drainage and sodium retention. Though EC levels were lower in soils currently under remediation or cultivation, sodicity persisted, with all tested samples exhibiting exchangeable sodium percentages above 15%. This highlights that short-term remediation efforts have limited effectiveness in addressing soil alkalinity and sodicity. Our findings emphasize the importance of incorporating soil texture into future remediation planning and support the need for expanded, systematic field studies to assess long-term outcomes across heterogeneous landscapes.

Keywords: saline-sodic soil, floodplains, soil texture, Inner Mongolia, soil remediation

1. Introduction

Soil salinization and alkalization have seriously threatened the arid and semi-arid areas of China, particularly in Inner Mongolia [1]. In Tuoketuo County (Figure 1a), located within the floodplain of the Yellow River, many tracts of land have been degraded by increasing salinity and alkalinity, rendering large areas unsuitable for agriculture [2]. Such degradation is closely linked to the region's geographic and climatic context. The area is characterized by alluvial soils formed in a floodplain

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environment, where sediments and irrigation water from the Yellow River and its major tributary, the Da Hei He, serve as significant sources of salts [3]. Moreover, the arid climate contributes to high evaporation rates, which, when coupled with a shallow groundwater table, promote salt accumulation near the soil surface [4]. These conditions create a landscape highly susceptible to salinization and alkalinization, particularly in poorly drained zones with finer soil textures.

Although the mechanisms of salinization and alkalinization are relatively well understood, the spatial variability of salt accumulation and the factors controlling regional soil salinity and alkalinity across this landscape remain poorly characterized. We hypothesize that soil texture plays a significant role in governing the spatial distribution of salinity and alkalinity in such floodplain systems, consistent with observations from other studies conducted in the Yellow River floodplains [5,6]. Specifically, areas closer to the river channels (e.g., natural levees) tend to have coarser soils due to the deposition of sand and coarse fragments during major flooding events. These coarser textures promote better drainage, thereby reducing salt accumulation. In contrast, areas farther from the river (e.g., backswamps) typically contain finer soils that are composed mainly of clay and silt particles, which impede drainage and enhance capillary rise, leading to increased salt retention. Therefore, we expect higher salinity and alkalinity levels to occur in finer-textured soils located at greater distances from the river. To test this hypothesis and advance the understanding of salt distribution in Tuoketuo County, we conducted a series of soil samplings across different distances from the Da Hei He river channel and analyzed key salt-related physical and chemical properties, including electrical conductivity (EC), pH, soil texture, cation exchange capacity (CEC), and exchangeable sodium (Na^+).

In recent years, several soil remediation and reclamation efforts—such as irrigation management, chemical amendments [7], and crop cultivation—have been implemented in Tuoketuo County to address salinization and alkalinization. However, the effectiveness of these interventions varies across sites, likely due to differences in soil texture, hydrology, and management practices. To assess these outcomes, our sampling strategy included both natural (unremediated) soils and areas under remediation or cultivation. This allows for a direct comparison of their physical and chemical properties, providing insights into the impact of remediation practices on soil salinity and alkalinity.

2. Methodology

2.1. Soil sampling

Soil samples were collected from a series of potentially salt-affected sites in Tuoketuo County, where the salinity and alkalinity levels were previously unknown (Figure 1b). Detailed information for each sampling location is provided in Table 1. A punch tube was used to extract samples at four depth intervals: 0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm. Following collection, the samples were air-dried at room temperature and passed through a 2 mm sieve to remove minor debris and coarse fragments for subsequent analyses.

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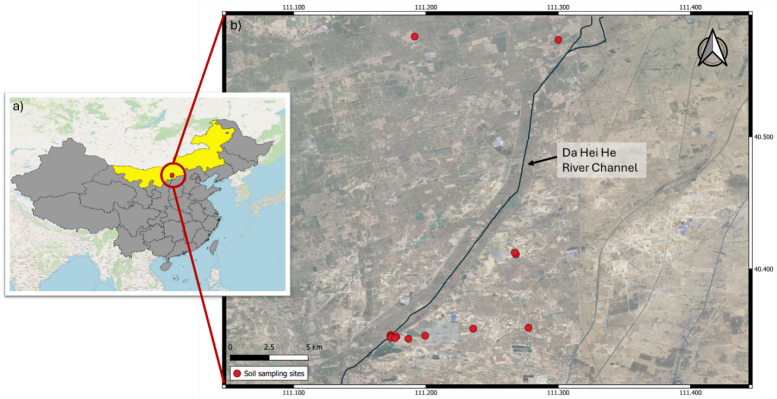

Figure 1: (a) Map showing the location of Inner Mongolia within China and Tuoketuo County's position within Inner Mongolia. (b) Map of soil sampling sites in relation to the Da Hei He river channel in Tuoketuo County

2.2. Soil physical and chemical analysis

Soil pH was measured using a pH meter in a 2.5:1 water-to-soil suspension. EC was determined using a 5:1 water-to-soil suspension, shaken for 3 minutes, and measured with a conductivity meter [8]. CEC was measured using the EDTA–ammonium acetate (pH 8.5) displacement method and quantified by titration [9]. Exchangeable Na^+ was determined using the ammonium chloride–ethanol extraction method and quantified by atomic absorption spectrometry (AAS). Soil particle size distribution was determined by quantifying three particle size fractions: sand (0.05-2 mm), silt (0.002-0.05 mm), and clay (< 0.002 mm), using the Bouyoucos hydrometer method [10].

2.3. Statistical analysis

Statistical analyses were conducted using RStudio. Pearson's correlation coefficients and simple linear regression were used to examine the relationships between soil EC and pH, as well as their associations with other physical and chemical properties. Two-sided, two-sample t-tests were performed to assess the statistical significance of differences between natural and cultivated/remediated groups. One-way ANOVA tests were conducted to test if there was significant differences in EC and pH across different depth intervals.

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Table 1: Summary of major salt-related soil physicochemical properties (EC & pH), texture, location, and land management status of samples collected in Tuoketuo County

Sample No.	Key Salt-related Soil Properties				Particle Size Distribution			Geographic Information			Treatment
	Surface EC (ds/m)	Average EC (ds/m)	Surface pH	Average pH	sand %	silt %	clay %	Distance from Channel (m)	Lat (°)	Long (°)	
1	0.49	0.57	8.54	8.46	38.5	46.8	14.7	1	40.36	111.19	natural
2	0.41	0.47	8.57	8.82	49.5	35.8	14.7	1	40.36	111.19	natural
3	1.30	0.96	8.38	8.38	51.3	37.0	11.7	15	40.36	111.19	cultivated
4	4.85	2.47	8.90	9.15	41.5	44.8	13.7	30	40.36	111.19	natural
5	4.41	3.94	8.75	8.85	40.5	41.8	17.7	100	40.36	111.19	natural
6	1.42	1.20	9.90	9.89	33.5	37.0	29.4	500	40.36	111.19	natural
7	4.78	2.86	8.96	9.17	43.1	31.4	25.5	1000	40.35	111.19	natural
8	0.63	1.22	8.86	9.10	38.8	39.6	21.6	1000	40.35	111.20	natural
9	2.69	1.95	9.11	9.21	37.5	41.0	21.5	3900	40.36	111.25	natural
10	3.91	2.60	9.20	9.18	28.1	44.6	27.3	3900	40.36	111.25	natural
11	4.87	5.80	8.41	9.07	25.3	40.0	34.7	3900	40.36	111.25	natural
12	0.12	0.33	9.05	8.71	NA	NA	NA	3900	40.36	111.25	cultivated
13	1.04	0.94	10.43	10.17	53.7	26.6	19.7	10000	40.36	111.29	natural
14	0.36	0.28	9.18	9.27	61.3	22.0	16.7	10000	40.36	111.29	remediated
15	0.37	0.55	9.42	9.47	53.3	30.1	16.6	>50000	40.42	111.28	remediated
16	2.46	1.42	9.41	9.64	46.4	30.6	23.0	>50000	40.42	111.28	remediated
17	4.31	3.06	8.63	9.23	31.5	41.5	27.0	>50000	40.58	111.31	remediated
18	1.44	1.24	10.31	10.24	37.5	35.2	27.3	>50000	40.58	111.20	natural

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3. Results

3.1. General characteristics of EC and pH

Based on measurements from all depth intervals, soil EC ranged from 0.12 to 6.99 ds/m, with a mean ± standard deviation (SD) of 1.71 ± 1.51 ds/m. Soil pH ranged from 8.27 to 10.51, with a mean ± SD of 9.31 ± 0.55. One-way ANOVA revealed no significant differences in EC ($F = 1.812$, $p = 0.15$) or pH ($F = 0.44$, $p = 0.725$) among the sampled depth intervals. Accordingly, no clear depth-dependent trends were observed. Therefore, given the lack of significant variation with depth and for ease of interpretation, only surface and average values of EC and pH over the 0–60 cm soil profiles were used in the subsequent analyses.

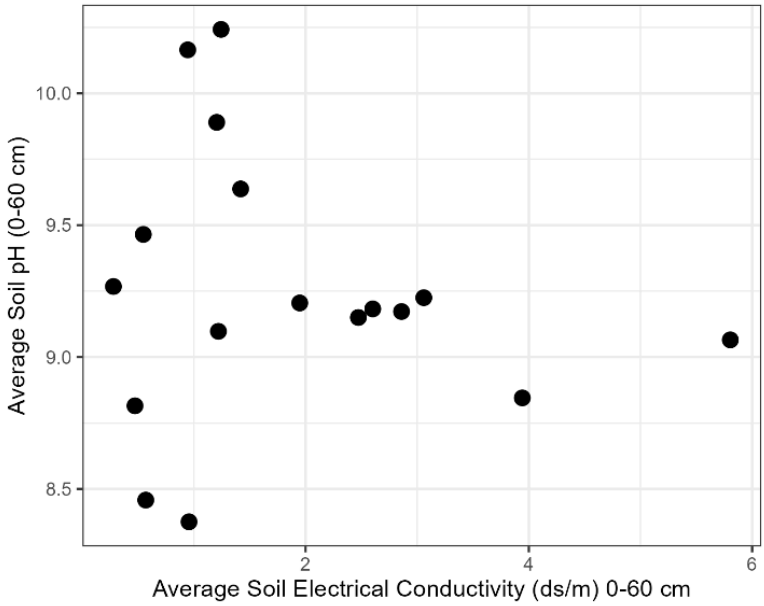

Figure 2: Scatterplot showing the relationship between average soil pH and average soil electrical conductivity (dS/m) in soils sampled from 0–60 cm depth ($r = -0.07$, $p = 0.79$)

No significant correlation was observed between soil EC and pH across the samples (Figure 2). This lack of association is consistent with findings from previous studies, which note that EC and pH are controlled by distinct geochemical processes and are often decoupled in salt-affected soils [11,12].

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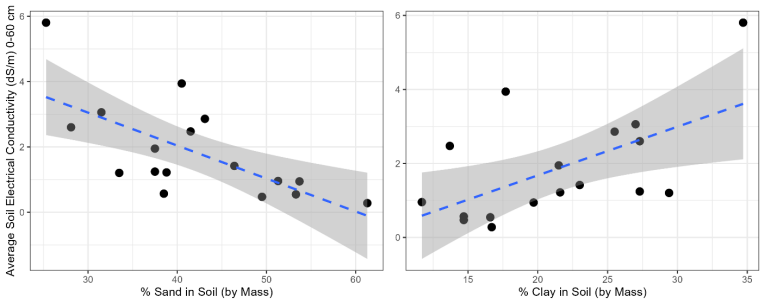

Figure 3: Scatterplots showing the relationships between average soil electrical conductivity (0–60 cm, dS/m) and the percentage of sand (left) and clay (right) particles in the soil. Dashed trendlines from simple linear regressions ($R^2 = 0.45$, $p < 0.01$ for sand; $R^2 = 0.34$, $p = 0.015$ for clay) are shown, along with their 95% confidence intervals

3.2. Soil texture as a control of EC and pH

Soil EC was found to be negatively correlated with the sand content and positively correlated with the clay content (Figure 3). Both correlations were moderately strong (r = -0.67 for sand and 0.67 for clay), and simple linear regressions confirmed that these relationships were statistically significant (Figure 3). These findings support our hypothesis that EC tends to decrease with increasing sand content, likely due to enhanced leaching and poor salt retention in coarse-textured soils, while higher clay content is associated with restricted drainage, higher groundwater tables, and increased salt accumulation in surface soil layers. Overall, the results suggested that soil texture likely plays a key role in controlling local patterns of salt accumulation across our sampling sites in Tuoketuo County, consistent with previous studies on similar landscapes [3,4,6,13].

Soil pH displayed a moderate correlation with the clay content (Figure 4) but showed no clear relationship with the sand content. Higher clay percentages were associated with elevated pH levels, suggesting greater alkalinity in finer-textured soils. This pattern may be attributed to the high CEC of clay particles, which enables them to retain more exchangeable Na^+—an important contributor to soil alkalinity, particularly under saline-sodic conditions [14]. Additionally, the restricted drainage typically observed in clay-rich soils can promote the accumulation of soluble salts and alkaline ions by limiting leaching, thereby sustaining the high pH levels over time [15].

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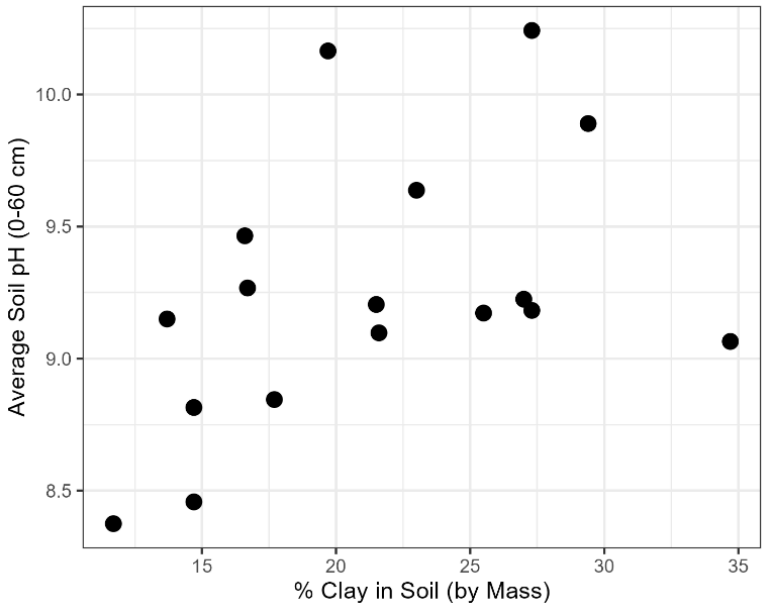

Figure 4: Scatterplot showing the relationship between average soil pH and average soil electrical conductivity (dS/m) the percentage of clay particles in the soils sampled from 0–60 cm depth (r = 0.46, p = 0.062)

The silt fraction, on the other hand, did not show a significant correlation with either pH or EC. This is perhaps unsurprising, as silts represent an intermediate particle size that does not strongly co-vary with either sand or clay and thus may not exert a consistent influence on salinity or alkalinity dynamics.

3.3. Current effect of remediation on soil salinity & alkalinity

Current remediation efforts on the saline–sodic soils in Tuoketuo County include both physical (e.g., vertical shaft and underground trench drainage systems) and chemical (e.g., amendments such as gypsum and calcium lactate) approaches [7,16,17]. In other areas, local farmers have practiced repeated cropping, typically with corn, as a low-cost and easily implemented biological remediation strategy to reclaim salt lands. Despite these efforts, our results showed no statistically significant differences in pH or EC between natural soils and those under remediation or cultivation (Figure 5).

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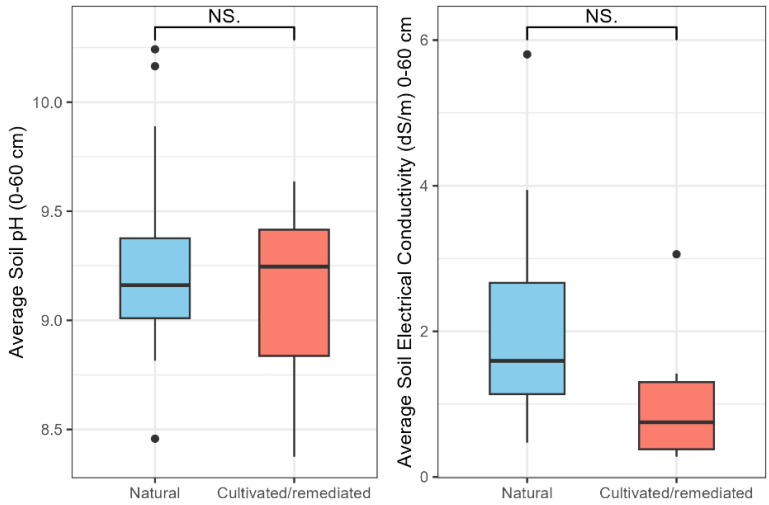

Figure 5: Boxplots comparing average soil pH (left) and average soil electrical conductivity (dS/m, right) from 0-60 cm between natural (n = 12) and cultivated or remediated soils (n = 6). Two-sample, two-sided t-tests indicated the differences between the two groups are statistically insignificant (NS., $p > 0.05$) for both pH and EC

However, when considering measures of central tendency—such as the median—an apparent difference in EC is still observed: natural soils (median EC = 1.6 ds/m) exhibited a higher median EC compared to remediated soils (median EC = 0.8 ds/m), even though this difference was not statistically significant. In contrast, no noticeable difference in pH values (median pH = 9.16 for natural and 9.25 for remediated/cultivated) was observed between the groups, whether assessed by mean or median (Figure 5). These findings suggest that while remediation may be beginning to influence salt concentrations, particularly in terms of reducing peak or average salinity levels, its effects on alkalinity may be less immediate or less pronounced.

To further assess the effectiveness of remediation efforts on soil alkalinity, particularly regarding sodium status, we measured the CEC and exchangeable Na^+ concentrations in five representative soil samples, including four from the remediated or cultivated sites and one from a natural site. From these values, we calculated the ESP (Table 2). Results showed a wide range in ESP across the samples, from 17.61% to 94.90%. Notably, all samples exceeded the sodicity threshold (ESP >15%), with three of them exhibiting extremely high ESP values (>60%), clearly indicative of severe sodicity [18]. These findings are consistent with the pH measurements, which suggest that despite ongoing remediation or cropping efforts, high levels of exchangeable sodium persist in some soils. This underscores the challenge of ameliorating sodicity in the short term and highlights the need for longer-term chemical or physical interventions that target not only soluble salts but also sodium bound to the soil exchange complex.

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Table 2: CEC and Exchangeable Na for selected soil samples

Sample No.	CEC (cmol/kg)	Exchangeable Na^+ (cmol/kg)	Exchangeable Sodium Percentage (ESP)
14	4.77	0.84	17.61
15	8.72	2.03	23.28
16	7.31	4.82	65.94
17	7.63	6.48	84.93
18	7.85	7.45	94.90

4. Discussion

4.1. Soil texture variability

Our results indicated that soil texture is likely a key factor influencing both soil EC and pH across the sampled sites. At the same time, the data revealed notable heterogeneity in soil texture across the saline–sodic soils of Tuoketuo County. For instance, sand content varied widely, ranging from 25.3% to 61.3%. To explain this internal variability in particle size distribution, we hypothesized that sediment dynamics within the floodplain alluvial system contribute to the observed spatial differences in texture. To test this, we established a transect of soil samples at varying distances from the Da Hei He river channel and compared their textures. A moderately strong correlation was found between distance from the river channel and both sand and clay content (Figure 6), supporting the idea that depositional processes along the floodplain influence soil texture and, consequently, salinity and alkalinity patterns. However, such a relationship did not hold beyond 4 km from the river channel, suggesting that other geomorphic or pedogenic processes—rather than fluvial deposition—may govern soil formation in more distal parts of the landscape. Additionally, the proximity of the Yellow River to the south of our sampling region may contribute further complexity to the sedimentary regime and could influence local soil texture patterns beyond the influence of the Da Hei He.

Several previous studies conducted in other regions have identified groundwater depth as a primary factor controlling regional soil salinity, particularly in arid and semi-arid floodplain systems where shallow water tables and high evaporation drive salt accumulation near the surface [3,4,13]. While our study did not directly measure groundwater depth, the observed strong relationship between soil texture and salinity provides a consistent and complementary perspective. Since soil texture regulates drainage and capillary rise, it indirectly influences the position and behavior of the groundwater table and the associated movement of salts within the soil profile.

Given the strong influence of soil texture on both salinity and alkalinity patterns observed in our study, it may be worthwhile to consider whether sandier soils offer more favorable conditions (e.g. better drainage and salt leaching) for effective remediation. However, this advantage must be weighed against the typically low water-holding capacity of sandy soils, which may limit plant-available moisture and require more precise irrigation management [15]. In contrast, finer-textured soils retain more water but are more prone to salt accumulation and sodicity due to poor drainage and higher sodium retention. These findings highlight the importance of taking soil texture into consideration when designing and implementing remediation strategies, particularly in heterogeneous landscapes like Tuoketuo County, where particle size distribution varies widely across short spatial scales.

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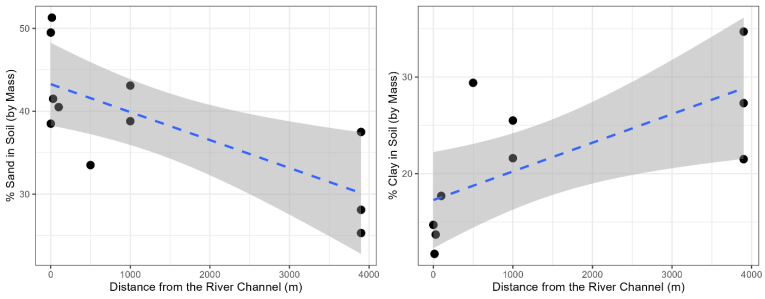

Figure 6: Scatterplots showing the relationships between sampling distance from the river channel of Dahei He and the percentage of sand (left) and clay (right) particles in the soil. Dashed trendlines from simple linear regressions ($R^2 = 0.53$, $p = 0.011$ for sand; $R^2 = 0.47$, $p = 0.02$ for clay) are shown, along with their 95% confidence intervals

4.2. Soil alkalinity: a persistent challenge

Our study demonstrates that soil alkalinization and sodification remain significant and persistent issues in the saline–sodic soils of Tuoketuo County. While there is evidence that remediation efforts are beginning to reduce soil salinity, reflected in a median EC below 1 dS/m (normal to slightly saline conditions) in the cultivated and remediated soils, alkalinity remains largely unmitigated. Elevated pH levels (>8.5) and high exchangeable sodium percentages (ESP >15%) were still observed in nearly all soils under remediation or cultivation. These findings suggest that while interventions may be effective in reducing soluble salts, they are less effective—at least in the short term—in addressing sodium accumulation and the resulting alkalinity. This underscores the importance of explicitly targeting sodicity and alkalinity in future remediation strategies [18].

The lack of statistically significant differences between the two groups may be attributed to the limited number of samples collected from remediated and cultivated fields, as well as substantial variability in both the remediation methods employed and the number of years since remediation. This heterogeneity was further compounded in the cultivated fields, where repeated cropping as a remediation strategy was highly localized and dependent on individual farmers' decisions, leading to inconsistent implementation across sites. Therefore, we advocate that future work prioritize more systematic, experimental field studies and increase sampling coverage to enable a more comprehensive and statistically robust evaluation of remediation outcomes.

5. Conclusion

This study characterizes the spatial variability of soil salinity and alkalinity in Tuoketuo County, Inner Mongolia. Through field sampling and laboratory analysis, we demonstrated that soil texture is a critical control on both salinity and alkalinity, with finer-textured soils exhibiting higher EC and pH values. While remediation may have begun to reduce salt concentrations in some cultivated or treated soils, its current impact on soil alkalinity and sodium status appears limited. Our results support the integration of soil texture considerations and strategies that can better address alkalinity into remediation planning and site selection. We recommend that future research prioritize long-term, experimental field studies and expand sampling efforts to capture landscape-scale variability. This will be critical for developing more effective and adaptable strategies to reclaim salt-affected soils in similar floodplain environments.

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